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hydrocarbon generation***

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Organic petrography and Rock-Eval characteristics of the Cenozoic fossil forest litter of Axel Heiberg Island, Nunavut, and their implications for hydrocarbon generation

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Abstract: An investigation of the organic petrography and hydrocarbon generative potential of the Eocene fossil forests of Axel Heiberg Island was conducted. Huminite (39–75%) and liptinite (17–42%) are the dominant macerals. Rock-Eval pyrolysis indicates moderate hydrocarbon potential in selected samples.

Neither Rock-Eval pyrolysis nor organic petrography alone can adequately assess the hydrocarbon generative potential of terrigenous source rocks. Rock-Eval pyrolysis measures anomalously high oxygen indices for unhumified samples. Organic petrography data do not necessarily directly correlate with the hydrocarbon potential of the fossil-forest sediments. When results from both methods are examined in combination, however, a more accurate interpretation of the nature of the organic matter and its hydrocarbon generative potential is possible.

Résumé : On a effectué une étude de la pétrographie organique et du potentiel de génération d'hydrocarbures des forêts fossiles éocènes de l'île Axel Heiberg. Les matières macérales prédominantes sont la huminite (de 39 à 75 %) et l'exinite (de 17 à 42 %). La pyrolyse Rock-Eval indique un potentiel de génération modéré pour les hydrocarbures dans certains échantillons sélectionnés.

Ni la pyrolyse Rock-Eval, ni la pétrographie organique utilisés seuls ne permettent d'évaluer adéquatement le potentiel de génération d'hydrocarbures des roches de source terrigène. La pyrolyse Rock-Eval permet de mesurer les indices en oxygène anormalement élevés d'échantillons non-humifiés. On ne peut pas nécessairement faire une corrélation directe entre les données de pétrographie organique et le potentiel de génération d'hydrocarbures des sédiments de la forêt fossile. Toutefois, en combinant les résultats des deux méthodes, il est possible d'arriver à une interprétation plus précise de la nature des matières organiques et de son potentiel de génération d'hydrocarbures.

INTRODUCTION

The fossil forests of the Geodetic Hills, Axel Heiberg Island, Nunavut (Fig. 1) have generated considerable interest among geologists and paleobotanists (Christie and McMillan, 1991, and references therein). The forests consist of well preserved, autochthonous wood and leaf layers, representative of the Middle Eocene high-latitude vegetational community, predominantly *Metasequoia*, with lesser amounts of *Glyptostrobus*, *Pinus*, *Larix*, *Pseudolarix*, *Abies*, *Quercus*, and *Betula* (Basinger, 1991). Cenozoic high-latitude forest vegetation may have provided much of the source material for the Beaufort Sea petroleum reserves. This report presents an investigation of the organic petrology and Rock-Eval pyrolysis characteristics of the sediments at this exceptional location.

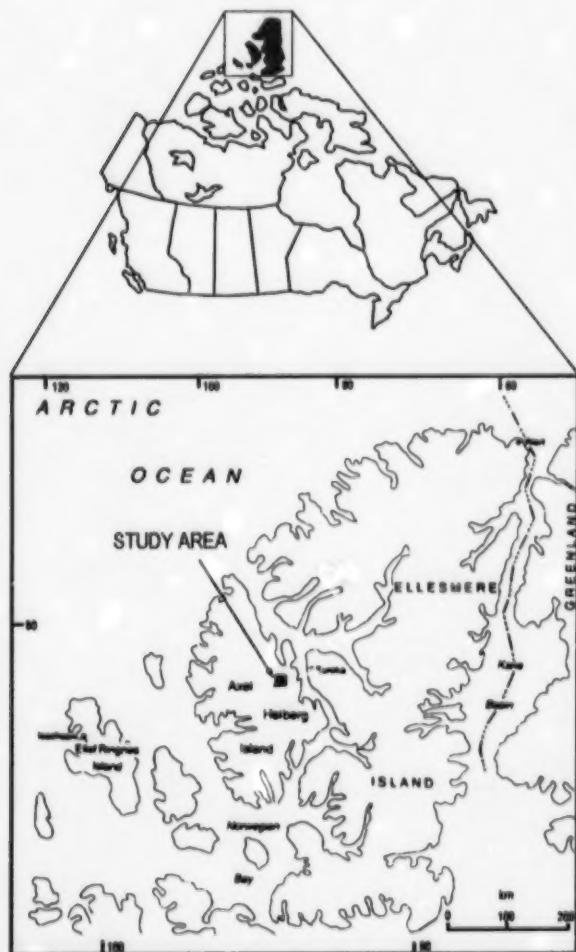


Figure 1. Location map of the sampling area.

GEOLOGICAL SETTING

The fossil forests of Axel Heiberg Island occur within poorly lithified conglomerate, siltstone, and sandstone strata of the Middle Eocene Buchanan Lake Formation of the Eureka Sound Group (Ricketts, 1991), deposited in a foreland setting during the Eurekan Orogeny (Bustin, 1982; Ricketts, 1991). The fossil forests are preserved as seams, from a few centimetres to several metres thick, of lignitic, organic-rich sediment within silts and sands deposited on the floodplains of meandering channels. The mode of preservation of these fossil forests is relatively unique amongst high-latitude Eocene forests, in that the wood, leaves, and cones have undergone very little permineralization and retain many of their original physical and chemical characteristics (Francis and McMillan, 1987; Christie and McMillan, 1991).

There are no modern analogues to the high-latitude fossil forests (Francis, 1991), although other high-latitude paleoforests have been documented (e.g. Dawson et al., 1975; Pole, 1999). The paleolatitude of the arctic Cenozoic forests was possibly as high as 78°N (McKenna, 1980), far above the present-day treeline. This indicates that the paleoclimate was considerably warmer than at present (Frakes, 1979; Wolfe and Poore, 1982) and that likely there was no polar ice cap. The unique geological setting and preservation of the fossil forest and the potential for resin-enrichment through the preponderance of *Metasequoia* and *Pinus* have implications for the potential generation of hydrocarbons in the Cenozoic sequences of the Canadian arctic (e.g. Snowdon, 1991).

METHODOLOGY

Sample locations of fossil forest litter are shown on Figure 2. The sample material can be classified as lignitic carbonerite (Stach et al., 1982) and ranges from true lignite (sample K) to lignitic shale and to silty shale.

For microscopy, the samples were air dried, crushed to particles approximately 3 mm in diameter, and impregnated in epoxy resin. Standard polishing techniques for coals were used to prepare the surface for analysis. The pellets were examined under reflected white and fluorescent light using a Zeiss Axioplan II microscope with a 40 \times magnification oil immersion objective (Halogen 100W HBO source, 400–460 nm excitation, 460 nm beam splitter, 470 nm barrier filter, type FF immersion oil). Point counts (400 counts per pellet) were conducted for each pellet. Maceral terminology follows nomenclature of the International Commission on Coal Petrology (1971, 1997) for brown coal. Random reflectance (%Ro) was measured on eu-ulminite B in all samples, using Zeiss Photan software.

Rock-Eval (5.0)[®] pyrolysis was conducted for two replicates of each sample following standard procedures (Espitalié et al., 1977). Parameters determined include total organic carbon (TOC), T_{max} , and S1, S2, and S3 values. These parameters were used to calculate the Hydrogen Index (HI) and Oxygen Index (OI).

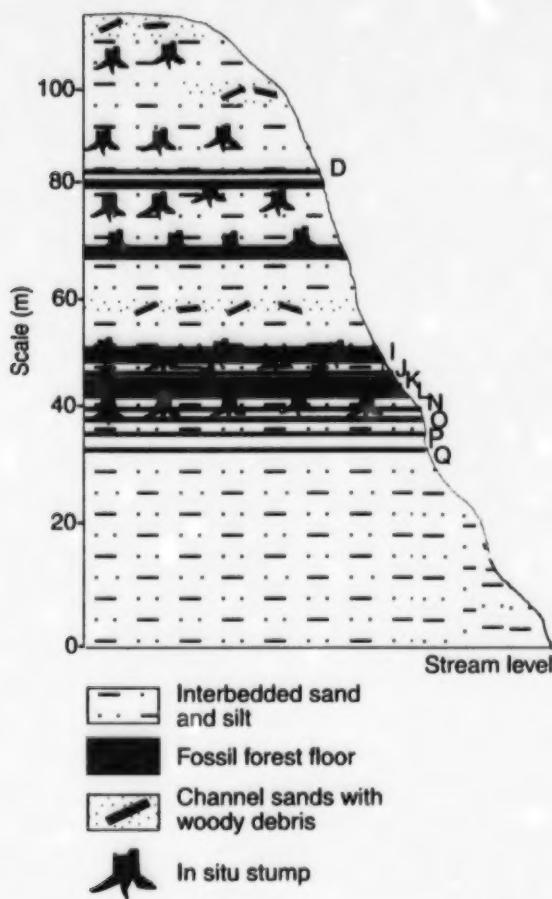


Figure 2. Section through the stacked forests exposed on Axel Heiberg Island. The sampling locations are indicated on the right by letters. Modified from Francis and McMillan, 1987.

OBSERVATIONS AND RESULTS

Microscopic and petrographic characteristics

The samples fall into the rank of lignite, with $\%R_o$ ranging from 0.24 to 0.29% (measured on eu-ulminite B).

Maceral assemblages are highly variable among samples. Huminite generally dominates the maceral assemblage, with abundant texto-ulminite and eu-ulminite (Table 1). Corpohuminite macerals (phlobaphinite, levigelite, and pseudo-phlobaphinite) are prevalent within most samples, reflecting the preferential preservation of peridermal tissues and the postdepositional migration of tannins within the plant tissues. Inertinite contents are very low (<1%, mainly funginite). Cutinite contents, ranging from 2% to 8%, reflect the leaf-litter origin of much of the sampled material. Moderate amounts of resinite are present within many of the samples, particularly K (13.5%), N (8%), O (12%), P (10%), and Q (10.5%). Resinite morphology varies and includes large, tabular particles with bright blue

to yellow fluorescence (Fig. 3a), low-fluorescing cell infillings (Fig. 3b), and oily-yellow- to green-fluorescing droplets found in association with corpohuminites (Fig. 3c). The following is a summary of the major petrographic characteristics of the nine samples examined. Unless otherwise stated, point-count results are volume percentages reported on a mineral-matter-free basis.

Sample D

Huminite macerals make up over 68% of the organic material (Table 1a). Several sporangia (preserved as sporinite) are present (Fig. 3d). Chlorophyllinite occurs throughout the sample (2.6%). Resinite is present in minor amounts (2.9%). Finely dispersed liptodetrinite and humodetrinite are often found within a matrix of clays. Brightly fluorescing resinite is common. Mineral matter (mostly clay minerals and quartz) is abundant.

Sample I

Sample I contains large and small wood fragments; however, on a volume percent basis, textinite is comparatively rare (1%) and corpohuminite is relatively more common (43.0%) (Table 1a). The resinite content is lower (5.7%) than for most other samples. Other liptinites are more abundant, including cutinite (12.5%), suberinite (7.2%), and bituminite (8.3%). Cutinite is usually intact, but the interiors of leaf remains are filled with corpohuminite or clay minerals.

Sample J

Preservation of huminite cellular structure is varied, with 8.7% textinite, 17% texto-ulminite, and 11% eu-ulminite (Table 1a). Low-fluorescing yellow resinite and corpohuminite are often found filling cells (such as in Figure 3b). The huminite macerals exhibit comparatively low fluorescence and fewer liptinites were noted (22.3%, the lowest of all samples analyzed).

Sample K

Sample K contains considerably less mineral matter than the other samples (Table 1b). Textinite and texto-ulminite are abundant compared with the other samples (9.3% and 22.3%, respectively) and corpohuminites are also common (Table 1a). Total liptinite content is 25.3%. Resinite (13.5%) commonly occurs as an infilling of cell lumina.

Sample L

The huminite content of sample L is lower than that of the other samples due to the relative lack of lignocellulosic (cell wall)-derived macerals (3.1% textinite, 9.2% texto-ulminite, 1.2% eu-ulminite). Brown-fluorescing bituminite is abundant (16.6%). Resinite exhibits a variety of morphologies and is moderately abundant (6.5%). Cutinite and suberinite are common (8.3% and 3.1%, respectively). Mineral matter is abundant (18.75% on a whole-sample basis; Table 1b); it is commonly mixed with liptodetrinites (7.7%) and humodetrinites (2.8%).

Table 1. Maceral composition of the samples, as determined by point counts
a) on a mineral-matter-free basis, **b)** on a mineral-matter-inclusive basis.

a) Sample	D	I	J	K	L	N	O	P	Q
textinite	4.4	1.1	8.7	9.3	3.1	4.6	0.9	10.1	10.0
texto-ulminite	12.0	11.0	17.0	22.3	9.2	10.0	10.3	13.4	17.8
eu-ulminite	1.5	2.7	11.0	6.3	1.2	15.0	2.1	0.9	2.1
corphuminite	44.2	43	39.4	34.6	31.8	32.3	40.4	42.3	31.7
humodetrinite	4.0	1.9	0.3	2.3	2.8	2.3	5.7	0.3	3.2
humogelinite	2.2	0.8	0.7	0.0	0.0	0.8	1.5	0.9	0.0
Total huminite	68.2	59.5	77.0	74.7	48.0	65.0	61.0	67.9	64.8
resinite	2.9	5.7	7.0	13.5	6.5	12.3	14.5	11.9	14.9
chlorophyllinite	2.6	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.0
liptodetrinite	5.8	1.5	1.0	1.5	7.7	3.1	6.3	0.6	5.3
cutinite	2.9	12.5	3.3	3.8	8.6	5.8	4.8	8.3	9.3
sporinite	5.5	2.7	2.7	1.8	5.5	1.2	4.8	1.2	1.1
suberinite	7.3	7.2	1.3	2.8	3.1	5.4	1.2	2.4	1.1
exsudatinitite	0.4	2.7	2.3	0.0	3.7	1.5	2.1	2.7	1.4
bituminite	2.9	8.3	4.7	2.0	16.6	5.0	5.1	4.8	1.4
Total liptinite	30.3	40.5	22.3	25.3	52.0	34.2	39.0	32.1	34.5
Total inertinite	1.5	0.0	0.7	0.0	0.0	0.8	0.0	0.0	0.7

b) Sample	D	I	J	K	L	N	O	P	Q
textinite	3.0	0.8	6.5	9.3	2.5	3.0	0.8	8.5	7.0
texto-ulminite	8.3	7.3	12.8	22.3	7.5	6.5	8.5	11.3	12.5
eu-ulminite	1.0	1.8	8.3	6.3	1.0	9.8	1.8	0.8	1.5
corphuminite	30.4	27.8	29.5	34.5	25.8	21.1	33.6	35.6	22.3
humodetrinite	2.8	1.3	0.3	2.3	2.3	1.5	4.8	0.3	2.3
humogelinite	1.5	0.5	0.5	0.0	0.0	0.5	1.3	0.8	0.0
Total huminite	46.8	39.3	57.8	74.5	39.0	42.3	50.5	57.0	45.5
resinite	2.0	3.8	5.3	13.5	5.3	8.0	12.0	10.0	10.5
chlorophyllinite	1.8	0.0	0.0	0.0	0.3	0.0	0.0	0.3	0.0
liptodetrinite	4.0	1.0	0.8	1.5	6.3	2.0	5.3	0.5	3.8
cutinite	2.0	8.3	2.5	3.8	7.0	3.8	4.0	7.0	6.5
sporinite	3.8	1.8	2.0	1.8	4.5	0.8	4.0	1.0	0.8
suberinite	5.0	4.8	1.0	2.8	2.5	3.5	1.0	2.0	0.8
exsudatinitite	0.3	1.8	1.8	0.0	3.0	1.0	1.8	2.3	1.0
bituminite	2.0	5.5	3.5	2.0	13.5	3.3	4.3	4.0	1.0
Total liptinite	20.8	26.8	16.8	25.3	42.3	22.3	32.3	27.0	24.3
Total inertinite	1.0	0.0	0.5	0.0	0.0	0.5	0.0	0.0	0.5
Mineral matter	31.5	34.0	25.0	0.3	18.8	35.0	17.3	16.0	29.8

Sample N

Much of the huminite is well humified in sample N, although some large, intact fragments are present (4.6% textinite, 10% texto-ulminite, 15% eu-ulminite). Corpohuminite macerals and resinite (12.3%) are abundant. Suberinite (5.4%) and cutinite (5.8%) commonly exhibit white fluorescence. Humodetrinite and liptodetrinite often occur in a mineral matrix. Mineral matter is very abundant (35% on a whole sample basis).

Sample O

Cell-wall-derived huminite macerals are rare in sample O. Corpohuminites are more common, as is humodetrinite (5.7%) and liptodetrinite (6.3%). Sample O contains numerous, brightly fluorescing, tabular resinites and abundant occurrences of resinite filling cell lumina, in which case it appears cracked with subdued fluorescence (14.5% total resinite).

Sample P

Sample P contains relatively large amounts of textinite and texto-ulminite (10.1% and 13.4%, respectively), with only traces of eu-ulminite (0.9%). Corpohuminite is abundant (42.3%), as are resinite (11.9%) and cutinite (9.3%). Bituminite with dark brown fluorescence (4.8%), suberinite (2.4%), and exsudatinitite (2.7%) are also present.

Sample Q

Sample Q is characterized by relatively abundant textinite (10%) and texto-ulminite (17.8%) and less corpohuminite (31.7%), compared with the other samples. Sample Q has the highest resinite content (14.9%) of all samples. Cutinite is also relatively abundant (9.3%). Liptodetrinite (5.3%) and humodetrinite (3.2%) are common and usually occur within a mineral matrix.

Table 2. Results from Rock-Eval pyrolysis.

SAMPLE	T _{MAX} C°	S1 mg HC/g rock	S2 mg HC/g rock	S3 mg CO ₂ /g rock	TOC %	HI	OI	HI'
D	422	7.5	37.2	36.0	23.1	161	155	194
	424	8.2	38.9	35.5	23.4	166	152	202
I	408	4.3	20.9	41.4	21.5	96	192	117
	411	4.0	18.0	42.6	21.8	82	195	101
J	409	4.4	25.6	45.4	28.7	89	158	105
	412	4.2	24.9	45.8	28.6	86	159	102
K	397	12.0	41.7	79.1	46.9	88	168	115
	394	12.4	40.1	77.4	46.1	86	168	114
L	412	14.3	62.1	34.0	29.9	208	114	256
	413	13.2	62.2	34.2	30.2	206	113	250
N	409	5.7	30.4	25.6	20.3	149	126	178
	411	5.7	30.3	25.6	20.6	147	124	175
O	394	14.4	75.5	34.4	33.5	225	102	269
	396	13.6	74.5	35.2	33.5	222	104	263
P	403	6.3	34.3	52.0	35.2	97	147	115
	409	6.5	35.2	50.6	35.5	99	142	117
Q	402	8.7	46.1	34.1	29.4	156	116	186
	404	9.8	49.7	33.5	29.1	170	114	204

DISCUSSION

Organic petrography and depositional environment

An earlier study of the organic petrography of lignites, carbonaceous shales, and related sediments from another location on Axel Heiberg Island was conducted by Goodarzi et al. (1991). The lignites and sediments were enriched in huminite, liptinite contents never exceeded 6%, and inertinite was usually rare. Based on the Tissue Preservation Index and the Gelification Index of Diessel (1986), the depositional environment was interpreted to be a forest swamp on a floodplain, in accordance with the sedimentological and palynological evidence (Goodarzi et al., 1991). The peats are interpreted to have been autochthonous to hypautochthonous. The maceral composition of the lignites and sediments studied by Goodarzi et al. (1991) differs somewhat from the results of the current study, particularly with respect to the liptinite contents. Such discrepancies may be attributable to lateral and vertical variability within the seams, so the lack of petrographic homogeneity between suites of samples is not surprising.

Evaluation of petroleum potential

Both Rock Eval and organic petrography are widely used to characterize organic matter. On the basis of petrographic and Rock-Eval data, the Type III kerogens in samples L and O have the highest liquid-hydrocarbon generative potential, that is, these samples have the highest S2 values, and high liptinite contents (particularly liptodetrinite, resinite, suberinite, and bituminite). Both samples are also characterized by low amounts of 'structured' huminite macerals

(textinite, texto-ulminite, and eu-ulminite). The lack of huminite macerals in a type III kerogen is considered to be advantageous for higher hydrocarbon expulsion potential from coal and type III source rocks. Using laser micropyrolysis, Stout (1994) noted that hydrocarbons can become trapped within a matrix of huminite, inhibiting oil expulsion.

The use of Rock-Eval or organic petrography alone to interpret the nature of organic matter can lead to erroneous assumptions. For example, sample K had the highest S3 value of all the samples, although S1 and S2 values are also relatively high. The high S3 value may be attributed to the hydroxyl, methoxyl, and carboxyl functional groups within the abundant lignin-derived textinite present in this sample, rather than to postdepositional oxidation. The S3 value should decrease as humification proceeds and the huminite molecular structure becomes increasingly condensed (e.g. Hatcher and Clifford, 1997).

In order to evaluate the contribution of liptinite macerals to hydrocarbon generative potential, plots were constructed of both individual maceral contents and total liptinite content versus HI. Plots of resinite and the total liptinite content versus HI are presented in Figure 5. As can be seen from Figure 5a, the correlation between resinite content and HI is very poor, whereas the total liptinite content versus HI shows a somewhat stronger positive correlation (Fig. 5b; $R^2 = 0.335$). The weak correlation between organic petrographic results and Rock-Eval results has been noted by other researchers in the past. Korth et al. (1990) cite the importance of the variety of liptinite present within the sample to the resulting hydrocarbon generation, as different macerals have different hydrocarbon-generating capacities. When hydrocarbon-generating capacities for each maceral type were measured and used to correlate organic petrography with Rock-Eval results, very high correlation

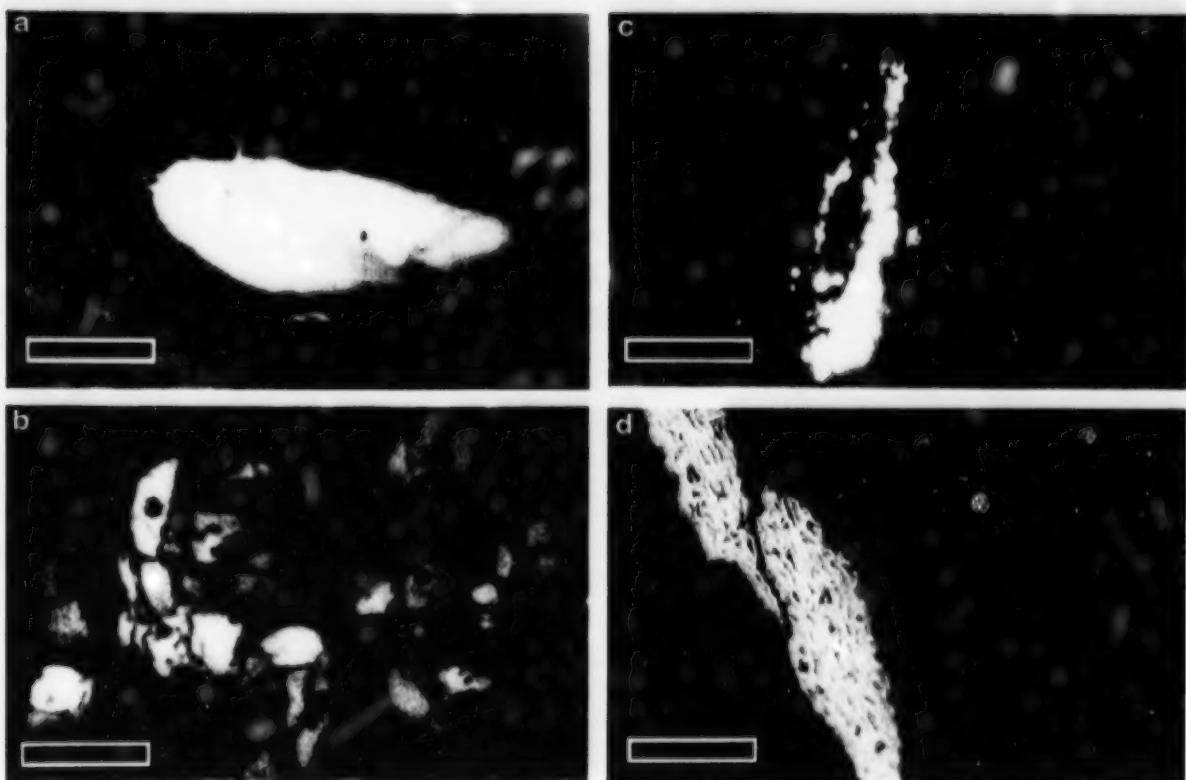


Figure 3. a-c) Examples of the variable morphologies of resinites found within the samples. a) Brightly fluorescing large blue tabular resinite (sample J); b) oxidized resinite filling cell lumina (sample N); c) brightly fluorescing droplets in association with huminite (sample J); d) an agglomeration of sporinite from sample D. Scale bar = 50 μ m.

Rock-Eval analysis

The total organic carbon content of the sample set ranges from 21 to 47 weight per cent, indicating that carbonaceous shale to shaly lignite make up the organic-rich fossil-forest layers. Rock-Eval analysis indicates that only a few of the samples contain modest amounts of hydrogen-rich kerogen (Table 2). Values of T_{max} vary (394–422°C), but are consistent with huminite reflectance values. Values of S1 range from 3.96 mg HC/g rock for sample I to 14.43 mg HC/g for sample O. The distribution of S2 values follow a similar pattern, with sample I having the lowest value (18.01 mg HC/g rock) and sample O having the highest value (75.52 mg HC/g rock). Values of S3 show a different pattern of distribution, with N having the lowest measured value and K having the highest. Hydrogen indices (HI) are greater than 200 for samples L and O. Some liptinites, such as resinite and suberinitite, are known to generate hydrocarbons at temperatures in the range of the S1 peak (for example, Fowler et al., 1991, Khorasani and Michelsen, 1991), so HI' ($S1+S2/total\ organic\ carbon$) was also calculated. The HI' values are higher than HI values (with a maximum value of 268 mg HC/g rock) and follow a similar pattern of distribution to HI. Oxygen indices (OI— $S3 \times 100/total\ organic\ carbon$) range from 103 mg CO_2/g TOC (sample O) to 194 mg CO_2/g TOC (sample I). When plotted on a pseudo-Van Krevelen diagram, these samples fall in the region of Type III kerogen (Fig. 4).

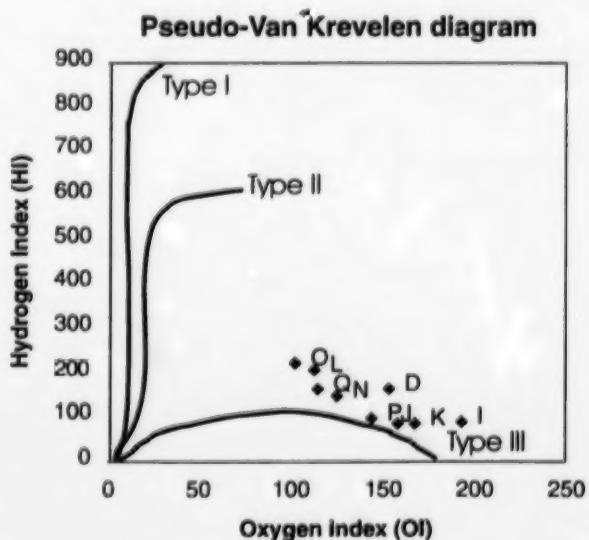


Figure 4. A pseudo-Van Krevelen diagram, with the fossil-forest material falling in the region of type III organic matter.

coefficients resulted. However, Korth et al. (1990) were using oil shales with very little maceral variation — the fossil-forest samples are too heterogeneous for this approach to be effective without considerable preliminary experimentation. The same authors also note the importance of interactions between liptinites and mineral matter during maturation.

When plots of HI are compared to plots of HI' versus resinite or liptinite (Fig. 5a, b), the graphs appear very similar. Only sample K seems to have increased in

hydrocarbon-generative potential relative to the other samples and this increase is very small. In these thermally immature samples, most of the S1-peak hydrocarbons may be derived from unpolymerized, primary organic matter (e.g. plant oils and resins), rather than from thermally generated hydrocarbons. However, since many of the macerals that contribute to terrigenous-sourced petroleum do so at very low levels of thermal maturity, the S1 peak should be included in the quantitative evaluation of terrigenous source-rock potential.

Figure 5 consists of two scatter plots. Plot (a) shows HI on the y-axis (0 to 250) versus Resinite content (%) on the x-axis (0 to 16). Plot (b) shows HI on the y-axis (0 to 250) versus Liptinite content (%) on the x-axis (0 to 60). Both plots include data points for samples L, O, D, N, P, J, and K. In plot (a), the points are scattered with no clear trend. In plot (b), there is a visible positive correlation, with points generally increasing from left to right.

Figure 5.

HI crossplotted with petrographic data. a) HI versus resinite content, showing little relationship between the two parameters; b) HI versus liptinite content, showing better correlation.

Figure 6 consists of four scatter plots labeled a, b, c, and d.
 Plot (a) shows HI' on the y-axis (0 to 300) versus Resinite (%) on the x-axis (0 to 16).
 Plot (b) shows HI' on the y-axis (0 to 300) versus Liptinite (%) on the x-axis (0 to 60).
 Plot (c) shows HI' on the y-axis (0 to 300) versus Resinites + ligno-huminite (normalized) on the x-axis (11 to 18).
 Plot (d) shows HI' on the y-axis (0 to 300) versus Liptinites + ligno-huminite (normalized) on the x-axis (0 to 50).
 All plots include data points for samples L, O, D, N, P, J, K, and I.
 Plot (a) shows a slight positive correlation.
 Plot (b) shows a strong positive correlation.
 Plot (c) shows a decrease in scatter compared to (a).
 Plot (d) shows an increase in scatter compared to (b).

Figure 6.

HI' crossplotted with petrographic data. a) HI' versus resinite: the hydrocarbon potential of K shows a slight relative increase, but otherwise the plot resembles that in Figure 5a. b) HI' versus liptinite: total liptinite content is more closely related to HI' than resinite content. c) HI' versus resinite plus ligno-huminite: a decrease in scatter relative to Figure 6a suggests that resinite absorption by huminite macerals has occurred. d) HI' versus liptinite plus ligno-huminite. Scatter has increased relative to Figure 6b, suggesting that huminite absorption is not a significant factor when liptinite macerals other than resinite are considered.

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Fowler et al. (1991) found that resinites in Type III kerogens impregnate huminite macerals, but are readily extractable, and so are not strongly bound to the huminites. In order to assess the importance of liptinite absorption to hydrocarbon-generative potential, plots were constructed of HI' versus resinite + cell-wall-derived huminite ('ligno-huminite') content, and total liptinite plus ligno-huminite content (Fig. 6c, d). The plot of HI' versus resinite content shows little relationship between the two parameters ($R^2=0.001$; Fig. 6a), similar to Figure 5a. The plot of total liptinite content versus HI' shows a somewhat stronger relationship ($R^2=0.354$; Fig. 6b). The weak relationship between resinite and HI' is attributable to the contribution made by the other liptinite macerals to hydrocarbon generation. The inclusion of ligno-huminite macerals renders a closer relationship between resinite content and HI' (Fig. 6c; $R^2=0.213$). However, the addition of ligno-huminite to plots of total liptinite content versus HI' actually increases scatter ($R^2=0.142$; Fig. 6d). This suggests that ligno-huminitic absorption may be a significant factor in hydrocarbon expulsion from resinites, but overall in this case, the impact is not substantial.

The higher detrital content of samples O and L suggests that some of the material analyzed may be of hypautochthonous origin, which is similar to the findings of Goodarzi et al., (1991). Although transport of organic matter prior to deposition is detrimental to coal quality, localized, 'short distance' transport of terrigenous source-rock organic matter may improve source-rock quality. Sedimentary transport may concentrate liptinitic material by promoting the biochemical (humification) and mechanical breakdown of huminites, resulting in the concentration of the more humification-resistant liptinites. The incorporation of sediment may also provide an environment from which the generated hydrocarbons are more readily expelled.

High-latitude terrigenous petroleum — the role of resinite

Resinites have distinctive chemical characteristics that vary between species and between the secretory organs that produce the resin. Such differences in chemical composition are evident in the resinites from the fossil-forest samples, as indicated by the variable fluorescence colours noted during the petrographic investigation (Khorasani and Murchison, 1988; Lin and Davis, 1988; Senftle and Larter, 1988) and the lack of petrographic evidence of oxidation, which also alters the fluorescence colour of the resinite (e.g. Goodarzi and McFarlane, 1991). As a result of these chemical differences between resinite types, different responses to maturation occur, both in terms of kinetics and hydrocarbon products (Snowdon, 1991). The variability in resinite chemistry within the samples may partly explain the poor correlation between resinite content and HI, as all resinite varieties were grouped together during the petrographic examination. Anderson and LePage (1995) conducted a Py-GC-MS analysis of fossil resins from Axel Heiberg Island and found that much of the resin is the diterpene variety, derived from *Psuedolarix*, although this

tree was relatively rare within the forest community. Resins were also identified from *Metasequoia* and *Pinus*. Under the classification systems described in Anderson et al. (1992), these resins fall under the category of Class I resins (diterpene resins based on polymers of labdatriene carboxylic acids).

Cenozoic type III kerogen is important in Canada because the Beaufort Sea petroleum reserves are derived from allochthonous, Cenozoic, terrigenous sources deposited in a deltaic setting (Snowdon, 1991), perhaps from vegetation similar to that found in the fossil forests. Terrigenous Cenozoic petroleum is not uncommon, representing 5% of the Earth's known oil reserves, however, most known deposits are in low-latitude regions and are paraffin-rich (Powell and Boreham, 1994). Petroleum from the Beaufort Sea region, however, is rich in naphthalene and aromatics and is believed to be derived from liptinites, particularly resinite, within type III organic matter (Snowdon, 1991). The hydrogen indices for these 'mature' source rocks were measured to be in the range of 130–250 (Issler and Snowdon, 1990), comparable to those measured in the fossil-forest samples, whereas hydrogen indices in the range of 220–300 are considered to be more common for terrigenous source rocks (Powell and Boreham, 1994). A hydrogen index of >220 has been suggested as the lower limit at which significant oil expulsion can be expected from type III kerogen (Powell, 1988). However, it has been shown that for terrigenous organic matter enriched in diterpene resinite, hydrocarbon generation and expulsion can occur in rocks with lower hydrogen indices (Snowdon, 1991). The degree to which resinite is labile varies, with diterpene resins generating hydrocarbons most readily and sesquiterpenes being less reactive (Snowdon and Powell, 1982; Snowdon, 1991). This factor helps to explain the discrepancies in biomarkers noted between the low-latitude and Beaufort-Sea oil reserves — sesquiterpenes are associated with the angiosperm-derived Damar resins (Anderson et al., 1992), which contribute to the formation of tropical, terrigenous petroleum (Stout, 1995).

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